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Characterizing Particle Size Distributions of Crystalline Silica in Gold Mine Dust

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Abstract

Dust containing crystalline silica is common in mining environments in the U.S. and around the world. The exposure to respirable crystalline silica remains an important occupational issue and it can lead to the development of silicosis and other respiratory diseases. Little has been done with regard to the characterization of the crystalline silica content of specific particle sizes of mine-generated dust. Such characterization could improve monitoring techniques and control technologies for crystalline silica, decreasing worker exposure to silica and preventing future incidence of silicosis.

Three gold mine dust samples were aerosolized in a laboratory chamber. Particle size-specific samples were collected for gravimetric analysis and for quantification of silica using the Microorifice Uniform Deposit Impactor (MOUDI). Dust size distributions were characterized via aerodynamic and scanning mobility particle sizers (APS, SMPS) and gravimetrically via the MOUDI. Silica size distributions were constructed using gravimetric data from the MOUDI and proportional silica content corresponding to each size range of particles collected by the MOUDI, as determined via X-ray diffraction and infrared spectroscopic quantification of silica.

Results indicate that silica does not comprise a uniform proportion of total dust across all particle sizes and that the size distributions of a given dust and its silica component are similar but not equivalent. Additional research characterizing the silica content of dusts from a variety of mine types and other occupational environments is necessary in order to ascertain trends that could be beneficial in developing better monitoring and control strategies.

Keywords

MOUDI; Respirable dust; Exposure monitoring

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INTRODUCTION

In occupational environments, exposure to respirable crystalline silica (hereafter silica) is an important concern, particularly in surface and underground mining. Prolonged exposure to high concentrations of silica-containing dusts can lead to silicosis (Leung *et al.*, 2012), an incurable fibrotic disease of the lung that is both debilitating and potentially fatal, as well as to other respiratory diseases including lung cancer (International Agency for Research on Cancer (IARC), 1997; National Institute for Occupational Safety and Health (NIOSH), 2002; Straif *et al.*, 2009). The Occupational Safety and Health Administration (OSHA) has recently released a new silica rule for general industry, decreasing the permissible 8-hour time-weighted average (TWA) exposure to a concentration of $50 \mu\text{g m}^{-3}$ (from $100 \mu\text{g m}^{-3}$) (81 CFR 16285). The current Mine Safety and Health Administration (MSHA) rule for the mining industry remains an 8-hour TWA concentration of $100 \mu\text{g m}^{-3}$, controlled indirectly by reducing the respirable dust standard (30 CFR 56.5001; 30 CFR 57.5001; 30 CFR 70.101; 30 CFR 71.101). While enforcement of such regulatory limits on the mass of silica that workers may be exposed to has resulted in a decrease in the occurrence of silicosis, its incidence has been recently documented in workers aged 15–44 (Bang *et al.*, 2015; Mazurek *et al.*, 2015), indicating that the current workforce continues to be exposed to dusts capable of inducing silicosis.

The presence of silica in respirable dust (e.g., as defined internationally by the ISO/ACGIH/CEN standard (1993)) has been documented in various mining environments around the world (Mikolajczyk *et al.*, 2010; Naghizadeh *et al.*, 2011; Park and Chen, 2013; Verma *et al.*, 2014). In the U.S., silica can be found in the respirable dust of coal mines, metal mines, and sand and gravel operations (Joy, 2011; Watts *et al.*, 2012; Cauda *et al.*, 2013). In coal mines, the primary source of mineral dust is the top strata above the coal seam (Schatzel, 2009); in non-coal mines, silica is a component of the dust present throughout numerous mining processes (Cares *et al.*, 1973; Cauda *et al.*, 2013); and in the industrial sand mining sector, crystalline silica in the form of sand is the main product of the industry. The percent silica (by mass) in such dusts has also been observed to be quite variable, ranging from less than 1% to over 30%, depending on the type of mining operation (Cauda *et al.*, 2013).

Accurate measurement of silica in respirable dust samples is essential to the monitoring and control of occupational exposure to silica. Established monitoring practices (Mine Safety Health Administration (MSHA), 2008; National Institute for Occupational Safety and Health (NIOSH), 2003a, b) are based on the analytical quantification of the mass of silica in a sample of respirable particles collected on a filter to determine the average silica concentration that a worker is exposed to over his or her shift. The most common analytical techniques used to quantify silica are X-ray diffraction (XRD) and infrared (IR) spectrometry (National Institute for Occupational Safety and Health (NIOSH), 2003a, b). Complementary analysis quantifies the mass of dust present in the respirable sample to determine the worker's exposure over a shift. The combination of the two analyses allows for the determination of the silica content of the respirable dust. However, this provides the integrated silica content over the entire range of particle sizes collected, and does not provide information about silica content within specific ranges of particle size.

As efforts to reduce incidence of silicosis continue, knowledge of the silica content of specific ranges of particle size will be useful for several reasons: 1) as noted by Qi *et al.* (2015), dust control technologies can be best developed and utilized when the size distribution of the dust and the silica content of different particle size ranges are well understood; 2) the analytical methods used to quantify silica in dust samples are most accurate when the size distribution of silica within the dust sample is closely matched to the size distribution of the calibration material (Huggins *et al.*, 1985; Pickard *et al.*, 1985); and 3) once inhaled, silica particles of distinct sizes may have variable impacts on inflammation and the development of fibrosis (Goldstein and Webster, 1966; Wiessner *et al.*, 1989; Mischler, 2013; Ohyama *et al.*, 2014). This may be further impacted by the enhanced penetration of smaller particles in the alveolar region of the lungs (Bartley and Vincent, 2011).

The size distribution of silica in mine dust has previously been investigated for coal mines (Page, 2003, 2006), with the intent of evaluating the standards used in the silica analysis of respirable dust samples collected in coal mines. However, there is a lack of literature on detailed examination of the silica content of respirable dust in non-coal mining environments, coupled with the degree of variability in silica content between different types of dust (Cauda *et al.*, 2013), has prevented a thorough understanding of particle-size related silica content. Sirianni *et al.* (2008) have noted that particle size distributions vary across dust-producing tasks and work sites, but that little has been done to explore this variation. As new technologies emerge and as the equipment used in industries such as mining continue to evolve, the properties of the dust generated – and the properties of the silica content of that dust – may also evolve, reinforcing the need to assess characteristics of dusts from a variety of regions and activities.

Qi *et al.* (2015) cite the lack of reliable characterization methods for size-related silica content of dust, as well as the variety of processes that produce crystalline silica-containing dusts with distinct qualities. They have described a method to assess size-dependent silica content of dusts as well as the generation rate of dust during the cutting of fiber cement siding.

We describe here a similar method for the characterization of size-related silica content in bulk or settled dusts, collected from mining work sites and re-aerosolized in the laboratory. We apply this method to three dust samples from the same commodity (but distinct geographical areas), to investigate if trends in size-related silica content are consistent among them. The results from this method demonstrate a straightforward approach by which dusts from a wide variety of real-world tasks or industries can be assessed with regard to silica content, while taking advantage of the stable conditions that may be achieved in a laboratory. To our knowledge, this is the first time that size-related silica content in mine dust has been evaluated for metal mining operations.

METHODS

Dust Collection and Treatment

Dusts from three gold mine operations (both underground and open pit) from Alaska, Nevada, and South Africa were selected for this study. The three dust samples were collected from settled bulk material in various areas of each mining operation. It should be considered that each dust represents a composite of dusts present at various locations on the mine site, and the sample is not intended to be representative of any particular process in the operation. In the laboratory, dusts were sieved to remove particles larger than 32 μm .

Independently, each sieved dust was then re-aerosolized in an RH-controlled calm-air Marple aerosol chamber (Marple and Rubow, 1983), using a TSI 3400A fluidized bed aerosol generator (TSI, Shoreview, MN). The aerosol chamber is 2.44 m high with hexagonal cross sections and an inside diameter of 1.19 m. The aerosol is introduced at the top of the chamber and thoroughly mixed in this region by the energy of the air jet entering at the side of the chamber. From the mixing region, the aerosol flows downward through a 10-cm-thick honeycomb structure where turbulence in the air is reduced, providing a low-velocity downward flow through the portion of the chamber where testing occurs. Before entering the chamber, the aerosol was neutralized by a TSI 3012A NRC Aerosol Neutralizer (TSI, Shoreview, MN). The chamber has been extensively used in recent years for studies on dust monitors (Volkwein *et al.*, 2004, 2006), and it is possible to control conditions inside the chamber such that the spatial variability is less than 5%.

Evaluation of Size Distribution and Quantification of Silica

The following methods of collection and analysis are summarized in the form of a flow chart in Fig. 1. The aerosol from each dust sample was characterized with two different spectrometers. A TSI 3321 aerodynamic particle sizer (APS; TSI) was used to measure particles from 0.5 μm to 20 μm , while a TSI scanning mobility particle sizer (EAD 3080; CPC 3010; SMPS; TSI) was used to measure particles from 14 nm to 673 nm. The SMPS was operated with a sheath air of 3 L min⁻¹ and aerosol flow rate of 0.3 L min⁻¹. Each instrument extracted the aerosol from the Marple chamber via a conductive tube (6-mm outer diameter). Dust samples were evaluated under a variety of chamber conditions (relative humidity; air flow; dust concentration) to ensure that size distributions remained consistent, independent of chamber condition. The resulting APS-aerodynamic and SMPS-electromobility size distributions were merged using the Data Merge Module (TSI), applying a lognormal fit for the composite size distribution.

Specific settings and corrections were applied in order to optimize the process of merging the two data sets. The density of each dust was estimated from the XRD analysis of the minerals, and was assumed to be constant with particle diameter; a shape factor of 1.2 was selected (Reid *et al.*, 2003; Kaaden *et al.*, 2009). The multiple charge correction for SMPS data and the efficiency counting correction for APS data were selected. Finally, the merged size distribution was exported as a function of the aerodynamic size of the particles, as this metric is more pertinent to the goals of this study.

Size-segregated samples were collected using a ten stage MOUDI-110R (MSP, Minneapolis MN), operating at the specified flow rate of 30 L min^{-1} (Marple *et al.*, 1991). The MOUDI was positioned outside the chamber and the aerosol was extracted via conductive tubing with 30-mm outer diameter. Samples for the construction of a particle mass size distribution (gravimetric analysis) were collected on 47-mm foil substrates for gravimetric analysis. Samples for silica quantification were collected on 47-mm PVC filters. All samples were pre- and post- weighed on a microbalance (Model UMX-2, Mettler-Toledo, Columbus, OH) in a temperature- and relative humidity-controlled environment.

Foil substrates for gravimetric analysis were greased in order to minimize bias due to particle bounce (Pak *et al.*, 1992). Particle size distributions were determined by inversion of gravimetric data, using the method described by Roberts *et al.* (2002) and calibration parameters for the MOUDI described by Marple *et al.* (1991). While greased substrates are effective in reducing particle bounce and re-entrainment, the use of grease is not suitable for chemical analysis of silica. In order to reduce the effect of the anticipated particle bounce while maintaining sample integrity, PVC filters were alternated with greased substrates in the MOUDI, so that positive bias due to larger particles bouncing onto lower stages was minimized as above. Importantly, negative bias due to particles bouncing off of the PVC filters was not addressed by this strategy. However, we assume that silica particles bounce off sample filters with the same frequency as do non-silica particles, and that particles bouncing off a filter are collected with nearly 100% efficiency on the greased impaction substrate that immediately follows. Thus, the collected proportion of silica remains unaffected. This strategy requires the collection of MOUDI samples for silica analysis in two tests when the PVC filters/substrates are alternated. The temporal stability of the size distribution of the dusts in the chamber assured a consistent sample for the MOUDI across both tests.

Sampling times varied by MOUDI stage according to the size distribution and approximate silica content of each dust, ranging from 30 minutes to 6 hours. This was done in order to collect sufficient material in size ranges where light particle loadings were anticipated (typically in the submicron size ranges), while avoiding overloaded samples in size ranges with anticipated heavy particle loadings. When possible, duplicate samples were collected by replacing PVC filters mid-test, so that samples could be analyzed by both infrared (IR) and X-ray diffraction (XRD) methods. In cases where it was not practical to collect multiple samples (due to long sampling times necessary to collect sufficient material), the most appropriate analytical method for that size range was selected (XRD for the largest three particle fractions, IR for the remaining fractions). Based on particle count data from the APS and SMPS testing, Stages 9 ($d_{50} = 0.097 \mu\text{m}$) and 10 ($d_{50} = 0.057 \mu\text{m}$) were not used in the MOUDI for IR/XRD sample collection, due to insufficient material in these size ranges for all three dust samples.

In addition to particle size-specific samples collected by the MOUDI, respirable dust samples were collected using 10-mm nylon cyclones at a flowrate of 1.7 L min^{-1} . Respirable dust samples were analyzed by X-ray diffraction using the Rietveld refinement (Rietveld, 1969) to identify and quantify mineral components of the respirable dust. Respirable samples were also analyzed by both IR and XRD to determine the integrated silica content

of the respirable dusts. Silica analyses were completed by the Mine Safety and Health Administration, Pittsburgh, PA, and RJ Lee Group, Monroeville, PA. Silica was quantified from samples collected on PVC filters via IR (MSHA P7 (2008)) and XRD (NIOSH 7500 (2003b)); two methods were used due to effects of particle size which can result in decreasing peak intensity with increasing particle size for IR and with decreasing particle size for XRD (Freedman *et al.*, 1974; Anderson, 1975; Bhaskar *et al.*, 1994). Due to the total volume of aerosolized dust that was needed to collect a valid sample (e.g., above the limit of quantification for silica) for each size fraction, it was not possible to collect multiple replicate samples. To evaluate reliability of the data collected, several considerations were made. First, mid-size particles samples (those collected on Stages 3–5) were analyzed by both IR and XRD methods, such that a comparison could be made of the silica mass fraction determined by each method. Because of the opposing nature of particle size effects in IR compared to XRD, samples in these size ranges should be subject to the least bias for both methods, and thus results are expected to be comparable for the two methods. We consistently found this to be the case.

Secondly, the silica composition of each size fraction of each dust was considered in the context of each “adjacent” size fraction. The size range of particles collected on a particular stage of the MOUDI partially overlaps with the size ranges collected on the stages above and below it. Due to this overlap, differences in silica composition from stage to stage should be somewhat moderated. More pronounced differences (for example, 1% silica in a size fraction, and 40% in the next smallest size fraction) might have indicated a problem during either sampling or analysis, but no such differences were observed.

RESULTS AND DISCUSSION

Mineral Composition and Size Distribution of Dusts

The results of the analysis of the minerals present in the three different dusts are summarized in Table 1. The dusts are composed of quartz silica as well as several other silicate minerals. The dust from Alaska also exhibits a substantial presence of both dolomite and calcite. The density of each dust was estimated from the mineral composition and was used in the process of merging data from the APS and SMPS spectrometers.

The particle number size distributions of each dust samples as a function of particle aerodynamic diameter are shown in Fig. 2. Each plot displays the composite particle size distribution from merged SMPS and APS data and the proposed fit distribution. For each dust sample, a unimodal distribution was selected to fit the composite data. The count median particle diameter (CMD) and geometric standard deviation (GSD) of each dust was determined from the fit distribution and the results are summarized in Table 2. The CMD was determined to be 1680 nm, 590 nm, and 498 nm for the dusts from Alaska, South Africa, and Nevada, respectively. Particle mass size distributions determined from inversion of gravimetric data collected using the MOUDI indicated a mass median diameter (MMD) of 5.17 μm for Alaska, 3.92 μm for South Africa, and 3.88 μm for Nevada dusts. Particle mass distributions for the three dusts are shown in Fig. 3(a); as the size distributions for the dusts from South Africa and Nevada are quite similar, the plots overlap completely. The

respirable fraction (European Committee for Standardization (CEN), 1993) of each dust sample is also shown, in Fig. 3(b).

With respect to both particle number and mass size distribution, the dust from Alaska is composed of the largest particles (CMD = 1680 nm, MMD = 5.17 μm), while the dusts from South Africa and Nevada are fairly similar to each other and composed of somewhat smaller particles (CMD = 590 nm, MMD = 3.92 μm , and CMD = 498 nm, MMD = 3.88 μm , respectively).

Silica Content of Dusts

Proportional silica (e.g., the mass of silica relative to the total dust mass) content for individual size fractions of each dust was determined from the mass of total dust (determined gravimetrically) and the mass of silica in the sample (determined by IR or XRD). Results are shown in Table 3; XRD results are given for the Inlet stage through Stage 2, and IR results for Stage 3 through the final collection filter. Fig. 3(c) shows the particle mass size distribution of the silica component of each of the dust samples, generated by applying the size-related proportional silica content in Table 3 to gravimetric data from the MOUDI and subsequent inversion of these values. The results indicated a median silica particle diameter of 5.83 μm (GSD = 1.69) for Alaska, 6.65 μm (GSD = 2.09) for Nevada, and 4.36 μm (GSD = 2.07) for South Africa dusts. Fig. 2(d) shows the respirable fractions of the silica distributions. Fig. 4 shows the proportional silica content of each dust as a function of particle size, in comparison to the size distribution of each dust (as shown in Fig. 3(a)). This plot was constructed by applying the proportional silica content for a particular size fraction to raw gravimetric data from the MOUDI for the same fraction, with no inversion of the data, and provides an illustration that the silica content of a particular dust is not consistent across different particle sizes.

The total dust and the silica component of the dust displayed similar mass size distributions for all three dusts; however, the MMD for the silica component of each dust was slightly larger than the MMD for the corresponding total dust, and the GSD of the silica size distributions were slightly smaller. While the statistical significance of these differences cannot be evaluated using the current data set, it is telling that the same trend is observed in all three dusts. Additionally, that the same trends are observed for dusts of moderately low silica content (Alaska) and fairly high silica content (South Africa) suggests that the trend is not dependent on the silica content of the dust.

It is logical that the particle size distribution of the silica component is narrower (indicated by the GSD) than that of the total dust. Silica particles are likely to be generated primarily by processes that fracture solid rock (e.g., crushing, grinding, blasting, cutting), whereas particles from a variety of sources comprise the total dust: re-suspended roadway and soil particles, particles from long-range transport, particulate emissions from vehicle and equipment, as well as mineral particles (both silica and non-silica) from the fracturing of rock. While the dusts generated by mechanical processes might be expected to have similar size distributions, dusts from other sources may have distinct size distributions.

High variability in the overall silica content of respirable dust samples collected from mining operations has been previously observed by Cauda *et al.* (2013). In an analysis of 3210 metal mine dust samples, the silica percent in the majority of samples ranged from 1.8% (5th percentile) to 25.8% (95th percentile). In agreement with these findings, our current investigation determined the percent silica of the respirable dust fraction (via MSHA P7 and NIOSH 7500) to be approximately 3.7% for the dust from Alaska, 13.8% for the dust from Nevada, and 18.5% for the dust from South Africa. It is important to consider that these dusts all came from gold mine operations. Between different size fractions of the same dust, proportional silica content is also quite variable, with the fractions of least and greatest silica content differing by a factor of approximately 4 for the dust from South Africa, and by a factor of approximately 10 for the dusts from Alaska and Nevada.

Strengths and Limitations

This investigation utilized settled bulk material collected from gold mines and re-aerosolized in a laboratory chamber. While the use of the laboratory environment enables significantly greater control over sampling conditions such as relative humidity, airflow, and dust concentration, the use of settled material does have limitations. Dusts collected from settled material are likely to be skewed towards larger particles, which settle more quickly than smaller, less massive particles. Additionally, in a study of the silica content of coal fly ash, airborne samples were found to have increased silica content relative to bulk samples collected in the same area (Hicks and Yager, 2006). Presumably this could be due to high silica content in smaller particle sizes for that particular dust, which are less abundant in bulk material due to longer settling times. However, this investigation assessed the silica content within specific size ranges of dust, and there is unlikely to be a marked difference in settling rate between silica particles and non-silica particles of a given particle size, provided that the particles have comparable densities. In this case, the estimated densities of the dust samples (see Table 1) are similar to the density of quartz (2.65 g cc⁻¹). While the size distributions of the total dust may not be entirely representative of airborne dusts in a mine, the use of settled material should not impact the size distribution of silica relative to the size distribution of the total dust.

The use of both IR and XRD methods for the quantification of silica is advantageous for particle size-specific samples, as the XRD method is considered to be more accurate for larger particles, and the IR method for smaller particles – thus, the combined results from these two methods are likely to mitigate analytical bias due to particle size effects. However, it is impossible to determine from this data if the discrepancy between IR and XRD results is purely the result of particle size effects, or if interference effects from the presence of other mineral interferences also contribute.

Finally, this study characterized the silica content of three gold mine dusts from three distinct geographical regions. It is not possible to extrapolate these results to other types of mines; however, additional investigations using this methodology to characterize dusts from other locations and types of mines may provide more generalizable data.

CONCLUSIONS

The variability observed in particle size-related silica content and the mass size distribution of silica particles within dust aerosol has implications for monitoring exposure to silica. Both the IR and XRD methods are subject to effects of particle size (Freedman *et al.*, 1974; Bhaskar *et al.*, 1994) that can negatively impact the accurate quantification of silica, particularly if the size distribution of the sample dust differs from that of the calibration material. Based on the results seen here, it is not sufficient to assume that all types of dust have similar size distributions (for comparison to the size distribution of the calibration material). These results represent three dust samples of the same type of commodity, but different trends or greater variability may be observed in samples from other types of mines. As such, additional efforts are necessary to characterize variability in size characteristics of different types of dust (and of silica in these dusts), and how such variability could impact bias in the quantification of silica for occupational exposure monitoring purposes.

We conclude that the mass size distribution of silica within these three gold mine dusts is similar to the mass size distribution of the overall dust, but that the size distribution of silica is slightly narrower and slightly skewed towards larger particles. Furthermore, the silica content of a dust is not constant between particle size fractions. These characteristics should be evaluated in dusts from different types of mines and from other occupational environments, using methodologies such as those described here and those described by Qi *et al.* (2015). Additionally, the effect of the size distribution of silica with regard to the accurate quantification of silica in respirable dust samples should be evaluated to determine if effects due to particle size may be contributing to exposure misclassification for workers.

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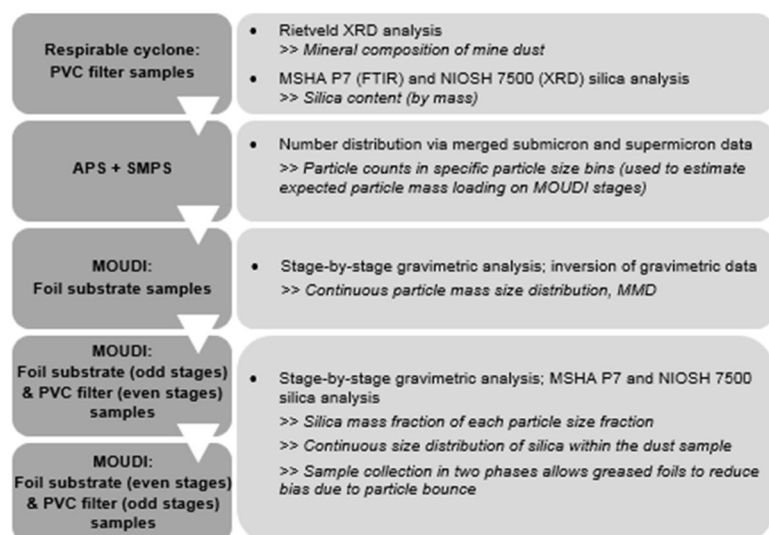


Fig. 1.
Flow chart of sample collection methods (on the left), analysis methods (on the right), and the type of data provided by each step.

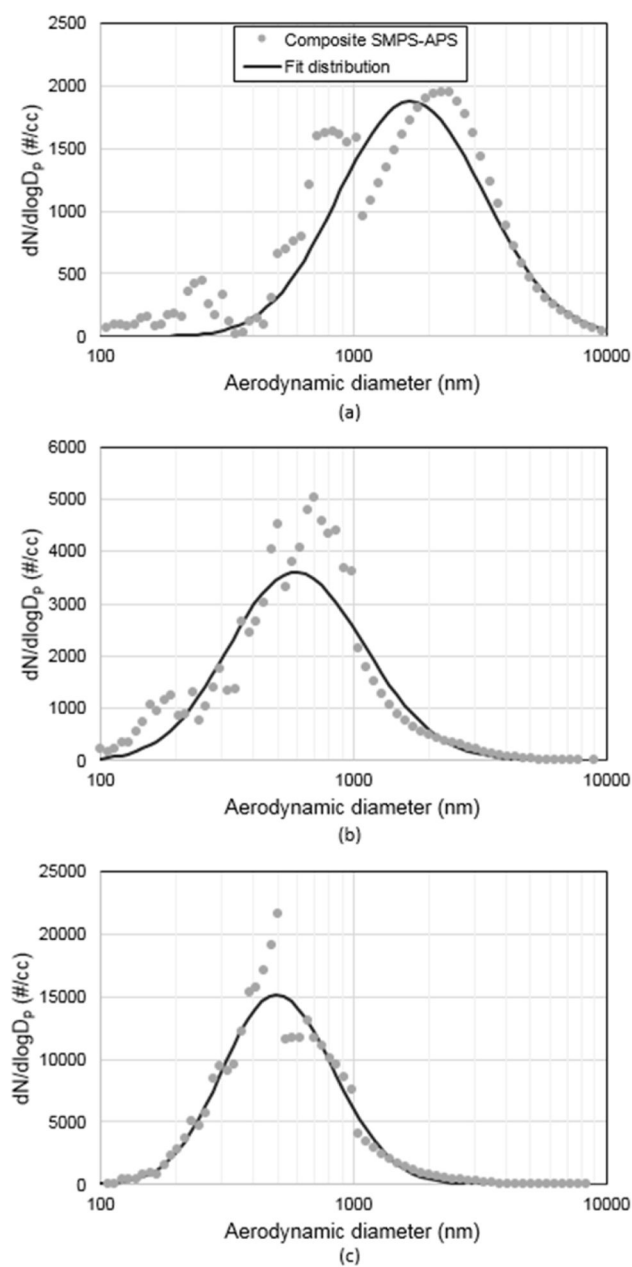
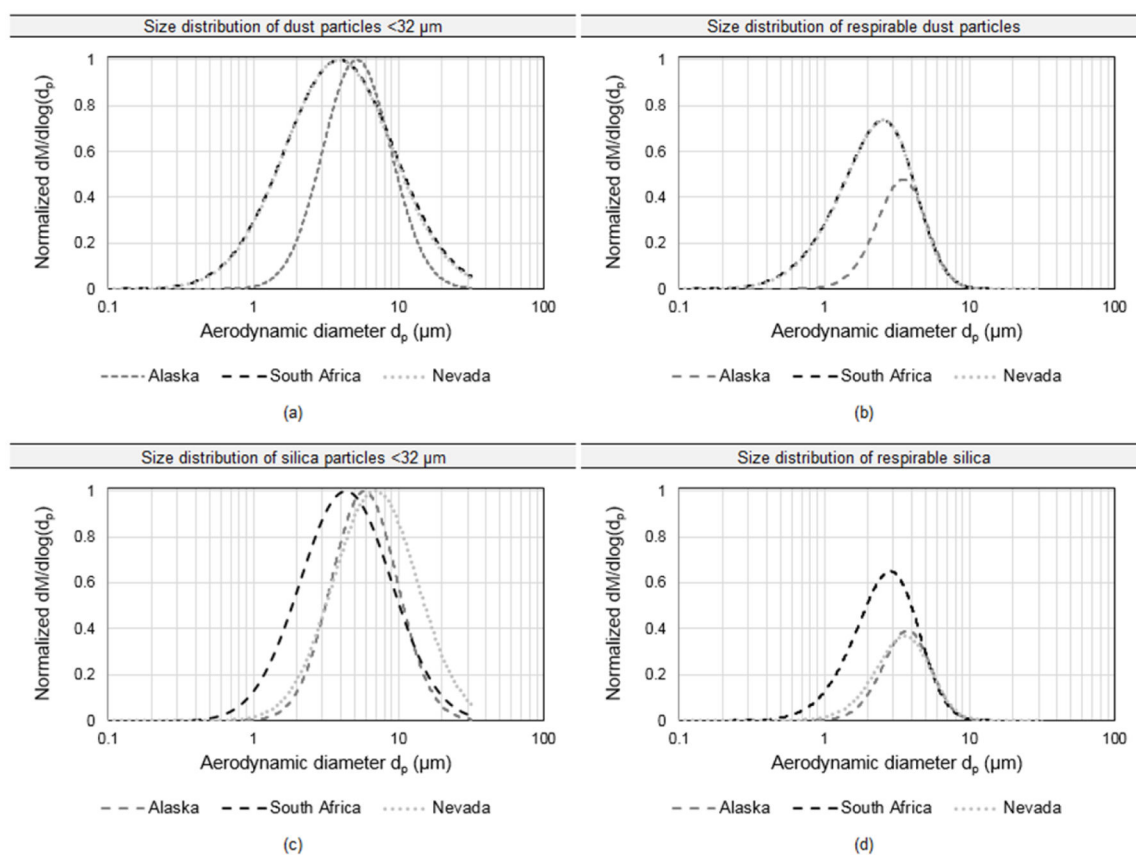


Fig. 2. Number particle size distribution from APS-SMPS merged data for dusts from Alaska (a), South Africa (b), and Nevada (c).

**Fig. 3.**

Particle mass size distributions of total dust < 32 μm (a), respirable dust (b), total silica < 32 μm (c), and respirable silica (d).

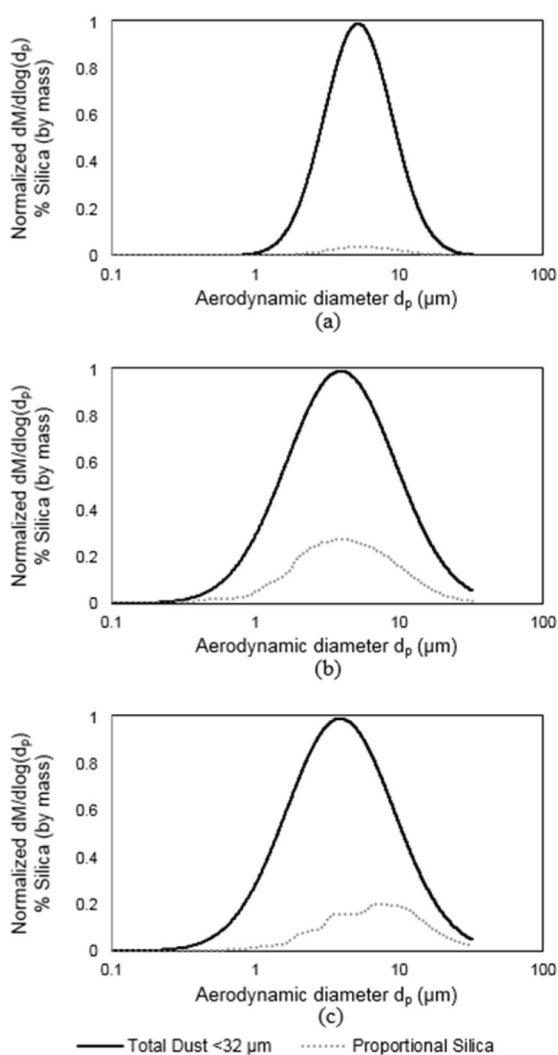


Fig. 4. Proportional silica content of the mass size distribution of total dust as a function of particle size, for dusts from Alaska (a), South Africa (b), and Nevada (c).

Table 1

Rietveld XRD analysis of mineral content of the three gold mine dusts. Phase Analysis (weight %)

Mineral	Alaska	South Africa	Nevada
Quartz	9	37	19
Muscovite	10	24	6
Chlorite	-	8	8
Pyrophyllite	-	26	-
K feldspar	-	4	-
Dolomite	51	-	-
Calcite	18	-	-
Gypsum	3	1	4
Alunite	-	-	55
Jarosite	-	-	8
Pyrite	7	-	-
Sphalerite	2	-	-
Wurtzite	1	-	-
Estimated density (g cc ⁻¹)	2.96	2.72	2.73

Table 2

Count and mass median (aerodynamic) diameter and geometric standard deviation for the three dusts.

	Alaska	South Africa	Nevada
CMD (μm)	1.680	0.590	0.498
GSD	1.96	1.94	1.72
MMD (μm)	5.17	3.92	3.88
GSD	1.72	2.39	2.36

Table 3

Mass percent silica composition for each size fraction (shown by MOUDI stage and corresponding cutpoint) of the three dusts.

MOUDI Stage	d ₅₀	Alaska	South Africa	Nevada
Inlet	18 µm	8.2	17.8	41.3
Stage 1	10 µm	5.3	27.8	42.9
Stage 2	5.6 µm	4.0	28.7	26.6
Stage 3	3.2 µm	3.6	27.4	15.7
Stage 4	1.8 µm	2.9	27.5	9.9
Stage 5	1.0 µm	1.5	20.2	5.0
Stage 6	560 nm	0.7	13.9	4.3
Stage 7	320 nm	-	30.8	-
Stage 8	180 nm	-	46.8	-
Final ^a	-	1.0	11.3	4.1
Respirable	4 µm	3.7	18.5	13.8

^aThe final collection substrate of the MOUDI is a filter that follows the last stage; it does not have a cutpoint but rather collects particles smaller than the cutpoint of the last stage. For Alaska and Nevada dusts, the last stage used was Stage 6, so the final filter sample contains particles smaller than approximately 560 nm; for Alaska dust, Stage 8 was the last used, and the final filter sample contains particles smaller than approximately 180 nm.